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Non-destructive structural integrity testing of finite plates based on the wave scattering at defects with sub-wavelength size

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Abstract

This paper describes a technique to magnify the scattering of a wave at a defect by using the natural behavior of a structure. The fundamental physical principle of the detection strategy as well as the way to exploit this principle for detecting defects are explained. The influence of the parameters defect location, defect size and natural frequency selected, is investigated in a numerical example considering a 1mm thick A3 Aluminum plate. The proposed defect detection strategy is based on the measurement of frequency response functions at a very limited number of response locations and is therefore very easy to apply. Furthermore, an experimental validation of the detectability of a square 4mm through thickness defect is performed. Due to its simplicity and the low number of sensors necessary, the strategy explained in this paper allows the detection of a defect very rapidly.

Keywords: sub-wavelength defect detection; wave scattering; non-destructive testing; magnification of wave scattering

1. Introduction

There is a large number of defect detection strategies based on different physical effects proposed in literature and applied to industrial problems. This paper focuses specifically on techniques using the dynamic behavior of the test structure. One group of such techniques are health monitoring strategies based on the change of modal parameters, such as natural frequencies, mode shapes or modal damping [1]. As these techniques draw information from modal characteristics, they work in a relatively low frequency regime. Besides their advantage of being applicable in many cases without additional excitation mechanisms, the main disadvantage is that global, modal parameters are not sensitive to small defects [2].

In contrast to modal methods, wave-based defect detection is usually performed at higher frequencies (multiple kHz to MHz). The main reason for this high frequency excitation is that the intensity of the interaction between an

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incident wave mode and a defect is strongly dependent on the ratio between the wavelength and the defect dimension. Multiple authors report that the wavelength needs to be at least comparable to the defect dimension or smaller [3,4].

Wave-based health monitoring strategies are used in many industries, starting from the structural health monitoring of oil and gas pipelines [4] and pipes in petro chemical plants [5], but also for the defect detection in smaller components, e.g. in composite parts in aerospace structures [6]. One similarity all those methods share is the need of multiple excitation points and specific excitation signals. The excitation of the structure becomes even more difficult, if the health monitoring strategy is based on the excitation of a single wave mode.

The defect detection strategy proposed in this paper is based on the excitation of a natural mode of a structure at a nodal point, e.g. with an impact hammer or a shaker. As will be shown, the scattering of the incident wave at a potential defect can be magnified by the reflection from the boundaries, similarly to what has been presented in [7] for the defect detection in pipes. Therefore the excitation can be applied at only one point, which overcomes the time-consuming application of a complex excitation mechanism. Furthermore, no expensive computation is needed to analyze the measured signals.

In order to explain the underlying principle of the defect detection strategy, at first the influence of the modal behavior of a structure on a wave field is described and the health monitoring strategy is derived in section 2. The following section 3 provides numerical examples, which are then validated in an experimental test in section 4. Section 5 presents the conclusions.

2. Magnification of wave scattering using natural frequencies

All variables in this section refer to the respective value at exactly one frequency. Facilitating readability, this is not further indicated.

If a structure with low damping is excited at one point, this excitation causes waves to propagate away from the source. The waves reach the boundaries, depending on their speed of propagation, where they are reflected. The reflected waves themselves propagate to other boundaries and are also reflected. This process repeats, until all waves present superposition to a stationary wave field Ψ_{intact}, which can be seen as a superposition of all modes in the structure, weighted according to the position, direction and frequency of excitation [8]. Equation (1) describes the wave field Ψ_{intact} as a function of different natural modes at the example of a rectangular plate with edge length L_x and L_y, hinged at all 4 edges (derived based on [8]):

$$\Psi_{intact} = F \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{\sin(n\pi x/L_x)\sin(m\pi y/L_y)\sin(n\pi x_0/L_x)\sin(m\pi y_0/L_y)}{f(\omega_0, \omega_{n,m})}, \tag{1}$$

where F is a scaling factor depending on the geometry (thickness, L_x, L_y) and the density of the plate, as well as on the input force. The integer numbers n and m characterize the order of the natural modes in x and y direction, respectively. The location of the excitation force is denoted by x_0 and y_0 and $f(\omega_0, \omega_{n,m})$ is a function describing the contribution of each eigenmode with eigenfrequency $\omega_{n,m}$ at the excitation frequency ω_0 and becomes small for $\omega_0 = \omega_{n,m}$.

If a unit point force is applied and Ψ_{intact} is evaluated at (x_1, y_1), then $\Psi_{intact}(x_1, y_1)$ can be interpreted as the frequency response function (FRF) from the excitation point (x_0, y_0) to the measurement position (x_1, y_1).

From Equation (1), it can be seen that the contribution of a mode shape to the wave field of an intact plate Ψ_{intact} becomes 0 if the terms $\sin(n\pi x_0/L)$ or $\sin(m\pi y_0/L)$ become 0, which means that the excitation acts at a nodal line.

If there is an inhomogeneity in a structure, the incident waves are scattered at this inhomogeneity. The scatterer can be considered as a secondary source with an amplitude depending on the scatterer itself (e.g. size, shape), the distance between defect and excitation, the background medium and the amplitude and frequency of the original point source.

Assuming a defect that is small as compared to the wavelengths of the propagating waves in the structure in the frequency range of interest, the influence of the scatterer on the mode shapes building the basis of Ψ_{intact} can be neglected. It is thus assumed that the same mode shapes can be used to predict the displacement field in the defected plate Ψ_{defect}, however, now considering an additional source at the defect location and thus different contribution factors for each of the modeshapes.

Assuming linearity of the structure, the overall displacement of the plate Ψ_{defect} is defined by the superposition of the fields resulting from each of the sources (the original one, and the one due to the scattering). Consequently, a mode shape, which is not excited by the original excitation can be excited due to the wave scattering at a defect if the defect is not located on a nodal point of that specific mode shape. In the case that the plate is excited at the frequency $\omega_0 = \omega_{n,m}$, the denominator $f(\omega_0, \omega_{n,m})$ becomes small and the contribution of this mode to Ψ_{defect} becomes relevant.

Due to this property, frequencies can be found at which mode shapes that do not contribute to the response field of the intact plate Ψ_{intact} do significantly contribute to Ψ_{defect}, although the scattering at the inhomogeneity may be very low. Though Equation (1) is only true for the described case, the underlying principle can be extrapolated to other structures with different geometry and boundary conditions.

The defect detection strategy proposed in this paper is based on the idea to perform the desired magnification using the natural modes of a structure as described in this section. This means that a structure is excited in a nodal point, so that the scattering at a defect, which is not located on a nodal point, is magnified and reasonably contributes to the displacement field.

3. Numerical example

The numerical examples at which the performance of the proposed method is studied are based on an Aluminum plate with dimensions 422mm × 297mm (thickness 1 mm, ρ = 2640 kg/m^3, E = 6.35·10^{10} N/m^2, μ = 0.33, η = 0.01‰) with free-free boundary conditions. The mesh size of the rectangular shell mesh is 2 mm.

In all cases studied in this section, the defect is modelled by removing elements to generate a 4mm by 4mm hole in the plate, while the location of the defect varies. The 3 investigated cases (A, B and C) are illustrated in Figure 1. The excitation is always acting at the center of the plate, as this position is a nodal point for many modes.

In this study, the purpose of the cases A and C is to demonstrate the technique, while case B is an example for the limitations as this defect is located on a nodal point of most mode shapes.

In order to find a suitable test-frequency for defect A and C, corresponding to an appropriate natural frequency and natural mode, the root mean square (RMS) of the FRF of the plate without defect is calculated. Furthermore, the modal behavior of the plate is analyzed. In Figure 2, the RMS FRF due to a point excitation in the center of the plate is shown as a solid line and all eigenfrequencies - including those that cannot be excited from the center of the plate - are indicated by dashed vertical lines. The frequency zone close to the directly excited resonance frequencies is not suitable for the defect detection, as in this case the contribution of the directly excited mode to the overall displacement is dominant. Therefore, in this example, natural frequencies in a range between 2050 Hz and 2100 Hz and between 2200 Hz and 2300 Hz are investigated with respect to their ability to detect the defects A and C, while case B serves as example of a defect that cannot be detected, as as both mode shapes show a nodal line at the location of defect B. As a consequence, the waves scattered at defect B are not expected to be magnified.

The analysis of the natural mode shapes in this frequency range shows that the most promising mode for the detection of defect A is the one with an eigenfrequency of 2051Hz (Figure 3 left) and the best suited mode for the detection of defect C is the one at 2225 Hz (Figure 3 right). These two modes are selected because they show a high displacement at the respective defect location and a nodal line at the excitation point.

In order to measure a maximum amplification of the scattered defect, the measurement points for each natural mode shape are defined at locations, with high displacement. Under the assumption that the defects are small and their

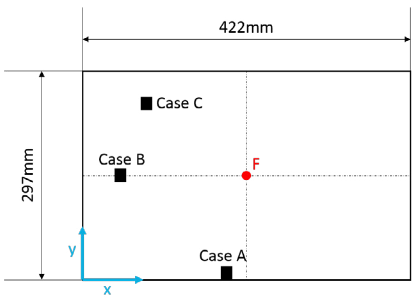

Fig. 1. Illustration of the plate and the 3 defect locations (A, B, C).

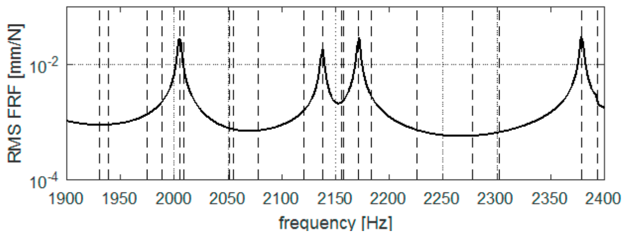

Fig. 2. FRF (solid line) and the natural frequencies (vertical dashed lines) of the non-defected plate.

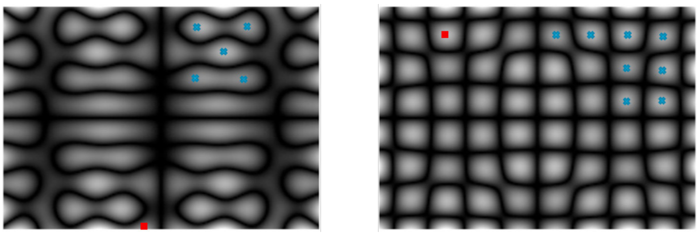

Fig. 3. Natural mode shape of the non-defected plate at 2051Hz (left) for the detection of defect A and of 2225Hz (right) for the detection of defect C. Locations of defects are indicated with red squares and measurement locations with blue crosses.

influence on the mode shapes is negligible, the symmetry of the plate can be used in order to minimize the necessary number of measurements, as shown in Figure 3.

Figure 4 shows the FRF for the intact plate (solid black line), the plate with defect B (o) and the plate with defect A and C (x), evaluated at the measurement points for the detection of defect A and C, respectively. As can be seen from Figure 4 top, the position of the resonance frequencies does not significantly shift due to the presence of the defect. This confirms that the influence of the defect on the natural frequencies is negligible. In consequence, it is assumed that also the symmetry of the modes is retained and measuring in only one quarter of the plate is sufficient.

The FRF corresponding to defect A (Figure 4 top left) shows, as expected, a resonance at 2051 Hz, while in the FRF corresponding to the intact plate and the plate with defect B, this resonance is not visible. In fact, the FRF of case B fully coincides with the FRF of the plate without defect over the entire frequency range under investigation.

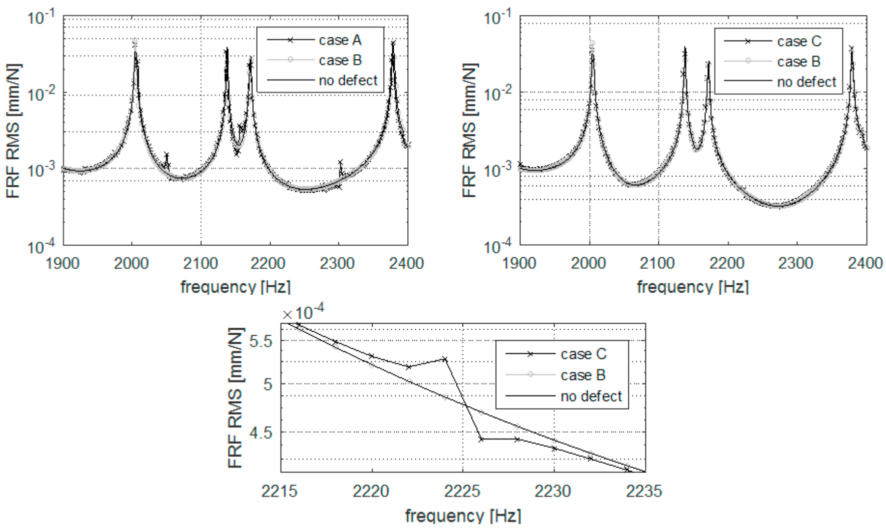

Fig. 4. FRF evaluated at measurement points for detection of defect A (top left), evaluated at measurement points for detection of defect C (top right) and a zoom into the frequency zone of interest for the detection of defect C (bottom).

This can be explained due to the fact that defect B is positioned in a nodal point of most mode shapes. Figure 4 top left also shows that additional resonance frequencies, e.g. at 2156 Hz and 2302 Hz, which are not excited in the non-defected case and case B, are excited in case A. The reason is that defect A is not located on a nodal point of these mode shapes and can therefore excite them.

In addition to the FRF, also the modal contribution factors of each mode for all cases are calculated. Those show that the peak at 2051 Hz in case A is caused by a significant increase of the modal contribution factor of the mode with the eigenfrequency 2051 Hz. The strong contribution of this mode only in case A supports the correctness of the theoretically developed defect detection method.

The influence of defect C (Figure 4 top right) is not as strong as that of defect A. Over the entire frequency range presented in Figure 4 top right, the FRFs of the non-defected case and the cases B and C are very similar. However, as can be seen from the zoom to the frequency range of 2215 Hz to 2235 Hz (Figure 4 bottom), the expected resonance at 2225 Hz is visible. This becomes evident when analysing the modal contribution factors of these cases. Although it can be shown that defect C is able to excite the expected resonance, particularly with respect to practical applications, its influence on the FRF is too small to be measured in a real experiment.

Further numerical simulations show that the peak value at 2051 Hz at defect position A increases with increasing defect size. But since the position of the defect in a real aplication case is not known and the magnification of the scattering strongly depends on this factor as well, the increase of the peak amplitude cannot be be directly linked to the defect's dimension.

4. Experimental validation

For the experimental validation, case A of section 3 is repeated experimentally. In order to suspend the plate there are two holes (3mm diameter) drilled at the position $x = 417$ mm and $y = 85$ mm and 212 mm, respectively. These locations nearly coincide with a nodal line of the mode that is planned to use for magnification. Therefore the influence of the suspension on the detection result is minimal. A point excitation normal to the surface is applied by an electromechanic shaker with band limited white noise, which is connected to the center of the plate with a stinger and an impedance head. The surface displacement of the plate is measured with a scanning laser-Doppler vibrometer at 2436 points on a regular mesh grid with 58 points in x-direction and 42 in y-direction.

In order to ensure repeatability, the experiment is repeated with the undefected plate and completely disassambled and reassembled between the measurements. Good repeatability can be found performing this test, although, except for the 4 resonances that can theoretically be excited by a force in the center (compare to Figure 4), additional peaks are present in the measured FRFs. The appearance of additional resonances can be due to a scattering of the incident waves at the two suspension holes, small geometrical imperfections of the plate and an imperfect excitation.

The comparison of the measured FRF of a plate with defect A and that of an intact plate is made in Figure 5. The FRFs presented are the RMS values calculated based on the same 5 measurement points as indicated in Figure 3 left. It is evident that the presence of the defect gives rise to a resonance at 2059 Hz. In addition, the level of the FRF around that resonance increases as compared to that of the intact plate. The experimentally acquired mode shape at 2059 Hz, based on the defected plate, shows a high similarity to the simulated mode of the intact plate presented in

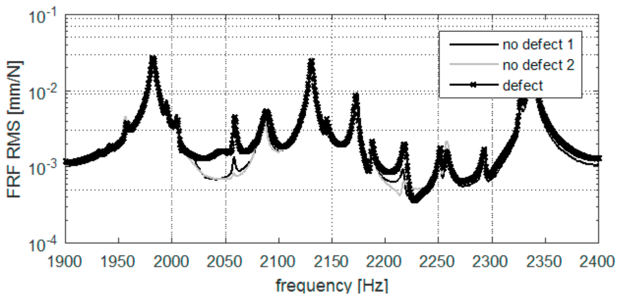

Fig. 5. Measured FRF of defected plate versus measured FRFs of non-defected plate.

Figure 3 left. Therefore it can be concluded that the effect of the defect in measurement and simulation is the same and can thus be used for the detection of this defect.

5. Conclusions

This paper discusses a technique to use the natural behavior of a structure to magnify the wave scattering at a defect. Therefore, the structure is excited in a nodal point of a modeshape chosen for the detection. Due to this excitation, in an intact structure, the chosen mode does not contribute to the overall displacement pattern. In case of a defected structure, the excited waves are scattered at the defect, which acts then as a secondary source that can excite the mode shape.

In order to choose the best suited mode for the detection of a defect, different parameters, such as the location of the defect, the location of excitation and the contribution of all mode shapes to the displacement at one frequency need to be taken into account. Furthermore, it is beneficial to measure the response at particular points, which depend on the wavemode chosen for the magnification.

At the numerical case study of a 1mm thick A3 Aluminum plate, 3 different defect locations are investigated with the result that defects at different locations can be detected using the magnification of different modes. Furthermore, the example showed that the magnification of the scattering depends on the location of the defect. This outcome can be used in a later step for the development of a defect localization algorithm. The numerical example demonstrated as well that the choice of the eigenmode used for the magnification must be done thoroughly in order to generate an effect that is strong enough to be measured in a real application.

The findings of the numerical study are validated at the example of a 1mm thick A3 Aluminum plate with and without a 4mm square through thickness defect.

The proposed defect detection strategy works based on the measurement of the frequency response function at a very limited number of locations. Depending on the application case, excitation at only one location can be sufficient, while there is no specific requirement on the excitation signal. Due to these characteristics, the defect detection strategy discussed in this paper is easy to use and delivers results very rapidly.

In its current form, as described above, the strategy gives only information about the existence of a defect. An algorithm to detect the location (or possible locations) of the defect based on the scattering and magnification by different natural modes is content of future research.

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